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16. Abstract

Some results of optical television measurements in the Zarnitsa-2 experiment are presented. The altitudes of the lower edge of artificial auroral rays were determined by the triangulation method and are compared with theoretical calculations of these altitudes based on the Jacchia and CIRA models of the atmosphere.

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ALTITUDES OF THE LOWER EDGE OF ARTIFICIAL AURORAL RAYS FROM BASE LINE MEASUREMENTS IN THE ZARNITSA-2 EXPERIMENT

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Introduction /3*

The Zarnitsa-2 experiment performed September 11, 1975, near Volgograd is one of a series of active experiments being carried out in the USSR. It is analogous in the nature of space activity to the Zarnitsa-1 experiment [1, 2] and is its further development in diagnostics technique. Thus, both ground-based optical and radiophysical measurements as well as onboard measurements were established more widely in the Zarnitsa-2 experiment [3].

A number of scientific research organizations participated in the preparation and performance of the experiment. These works were coordinated by Izmir AN SSSR;** the scientific director of the experiment was Doctor of Physical and Mathematical Sciences I. A. Zhulin; the chief engineer was V. S. Dokukin.

Data obtained with the help of ground-based high-sensitivity television installations of the Institute of Space Research A.S. USSR and T. G. Shevchenko Kiev State University were used in the presented work.

In the Zarnitsa-2 experiment, a beam of electrons was injected from a MR-12 meteorological rocket. The injector operated in two modes with a pulse length of 0.87 and 0.08 sec and a gap of 0.72 sec. The first mode with electron energy E_I = 9.5 keV and current $\mathfrak{J}_1 = 300$ mA was carried out on the ascending part of the rocket trajectory in the altitude range from 110 km to 135 km; the second mode with energy E_2 = 7.2 keV and current $\mathfrak{J}_2 = 450$ mA began at an altitude of 135 km and continued to the entrance of injector into the dense layers of the atmosphere. After apogee (H_α =156 km), on the descent portion of the trajectory, beginning at an altitude of 147 km to 128 km, a cesium plasma generator with an /4

*Translator's note. Numbers in margins indicate pagination in original foreign text.

** Izmir AN SSSR= Institute of Tenistrial Magnetism, the Ionosphere and Radio Wave Propagation, Academy of Sciences USSR

effective current $\sim$ 6A operated for charge compensation. The electrons were injected at an angle of 120° with respect to the longitudinal axis of the rocket. Due to rotation of the rocket and precession of the axis of rotation, the initial pitch angles of injection varied from 28° to 90°, i.e. the electrons were injected primarily in the lower hemisphere. The set of onboard measuring instruments included:

1. Vol't-M electron detector E = 30 keV (IKI AN SSSR);
2. Volna radio emission detector (IZMIR AN SSSR);
3. Pole rocket potential gauge (IZMIR AN SSSR);
4. Ushba-M intermediate-energy electron spectrometer E_e = I + 10 keV (IKI AN SSSR).

[IKI AN SSSR = Institute of Space Research, Academy of Sciences USSR]

With the interaction of the injected electrons with the atmosphere, optical radiation is generated - artificial aurora (AA), which was recorded in the previously performed experiments [1,4,5]. Besides the artificial aurora observed in the form of a thin ray, illumination of the near-rocket region (NRR), first observed in the Zarnitsa-1 experiment, was also observed in the Zarnitsa-2 experiment. Optical observations in the Zarnitsa-2 experiment were carried out from two points (optical equipment of IKI AN SSSR was placed at point M, that of the Astronomy Department of Kiev State University was placed at point E) with the help of high sensitivity television equipment. The TV equipment was based on commercial equipment; tubes of the type LM-217 (superopticon with brightness amplifier) were used as the transmitting tubes. The staggered scanning, 625 lines, 25 frames/sec was used. The image from the monitor screen was photographed at a rate of 5 frames/sec. Thus, five television frames were recorded in one photograph, which improved the signal/noise ratio (as compared to one television frame). A Jupiter-3 objective (D:F = I : I.5, F = 50 MM) providing a field of view 20°x30° and threshold sensitivity $\sim 9.5^m$ was used as the input objective of the TV camera at point M. A Helios-40 objective (D:F = I:I.5, F = 85 MM) providing a field of view 12°x16° and permitting recording stars of 10^m at the observation limit was used at point E. It is also necessary to note that, besides the main task of recording the AA and NRR images, the auxiliary task of orientation (guiding) of modulation photometerrs in the AA emission lines, which have a small field of view $\sim 6°$, was performed at point M with the help of the television installation. The modulation photometers were mounted on the single /5

rotating device along with the television camera; the centers of the fields of view of the photometers and TV camera coincided, which permitted correcting the photometer direction by observing the AA and NRR images on the television screen.

2. Experimental results

The AA and NRR were recorded in the Zarnitsa-1 experiment only from one ground point. Thus, besides the optical data, radar trajectory measurements had to be used to determine the altitudes of the lower edge of the artificial auroral rays and the direction of the magnetic field [6]. In the Zarnitsa-2 experiment, the AA rays were reliably recorded from two points, which permitted determining the altitudes of the lower edge of the artificial auroral rays by the baseline method on the basis of the optical data only. During the experiment, thirty baseline photographs of the AA rays arising during the long pulses of electron injector operation were taken. The equatorial coordinates (α, δ) of the lower edge of the AA ray were determined relative to the nearest background stars with known coordinates [7], by using /6 the six-constant method [8]. A computer program for determining the altitudes of the lower edge of the AA rays (cf. appendix) was compiled on the basis of well-known methods for determining the position of objects from baseline photographs [9,10]. The accuracy in measuring the position of an object with respect to reference stars differs (different input objectives and somewhat differing parameters of the installations): 0.I° for photographs of point M. The errors in determining the altitudes are caused by inaccuracy in determining the coordinates of the object with respect to the stars from the photographs.

The accuracy in plotting the coordinates depends strongly on the nature of the object and its brightness, the amount of light energy on the resolution element of the television installation in this case. The gradient of the change in brightness along the ray for the lower edge is high, but the change in brightness of the ray and the threshold sensitivity of the television installation (over the image field) leads to a change in the position of the lower edge. The subjective error in setting the measuring telescope cross hair on the lower edge of the AA is higher than in setting onto a star or NRR and also depends on the brightness of the rays. This accuracy in determining

the coordinates of the lower edge of 0.I° gives an absolute error in altitude of 2.8 km in the final result. Such errors are considered completely acceptable in measuring the altitudes of the lower edge of natural auroras even with the use of longer focal length cameras.

The main experimental results are presented in Figure 1, where the values of the altitudes of the lower edge (left altitude scale) and the altitude of the rocket with the injector (right scale) at corresponding times are given. Calculations are also presented for the maximum penetration depth of electrons with E = 7,0 keV for the CIRA-65 and Jacchia-71 models. The values of the residual range taken from [11]: E = 7,0 kev, $\tau_0(T) = 1{,}57 \cdot 10^{-4}$ gm/cm^2.

One can state by comparing the experimental results with the theoretical calculations carried out with the CIRA-65 model of the atmosphere that they agree well within the error limits. /7

The measurement error imposes limitation on the accuracy in calculating the electron energy loss due to the rocket potential, collective processes, (Beam-plasma discharge [12,13,14,15], plasma oscillations, etc.) and internal gravitational waves of the atmosphere [16] and permits determining only the upper limit of the assumed losses. This value was esimated by comparing the altitudes of the lower edge of the ray with the theoretical values for various energies and is about 2 keV. Consequently, the rocket potential cannot exceed this value.

However, for a more detailed study of the physical processes leading to anomalous penetration of the electron beam into the atmosphere, it is necessary to significantly increase the accuracy of the method, which is achieved by increasing the spatial resolution of the AA photographs (by using objectives with long focal lengths) and more accurate determination of the geographical coordinates of the baseline points.

The fundamental possibilities and the promise of ground-based triangulation optical measurements for studying physical effects arising in the upper atmosphere with artificial effects are shown in this work.

The authors express thaks to colleagues of IZMIR AN SSSR for coordination of the basic organizational works and V. G. Gunkin for help in carrying out the experiment.

Appendix /8

The problem of determining the altitudes of the lower edges of artificial aurora is solved with consideration of the curvature of the surface of the earth. The surface of the earth is taken as the surface of a sphere with radius R_o = 6381 km. It is easily verified that an accuracy of several kilometers have practically no effect on the final results. Fig. 2 gives the relative position on the surface of the earth of the optical observation points M and E, the north pole and the projection of the trajectory of the lower edge of the AA ray on the surface of the earth - AB.

Let us consider (fig. 3) the plane triangle EMO with base EM = d and altitude O coinciding with the object. Strictly speaking, EM $\neq$ d since d is the distance between the points E and M measured along the surface of the earth, while EM is the distance between the points along a straight line. However, the difference between the arc and chord for distances $d < 70$ km is $\sim d \cdot 10^{-6}$ which is insignificant in this case.

The parallax angle P equals the angular displacement of the object on the celestial sphere with a shift from point E to point M. The relation between the parallax angle and the coordinates of the object α_1, δ_1, α_2, δ_2 measured at the same time from points M and E is given by the law of cosines:

$$\cos p = \sin\delta_1 \sin\delta_2 + \cos\delta_1 \cos\delta_2 \cos(\alpha_1 - \alpha_2) \cdot \tag{1}$$

It is necessary to determine the angle β in the triangle EMO. The distance of the observation point E to the object O is then

$$D = d\frac{\sin\beta}{\sin p} \,. \tag{2}$$

There are different methods for determining the angle [5,6,9,10]. /9

However, a majority of them are based on the geographic coordinates of the observation points being precisely known. In this case, the geographical coordinates are known approximately and it is more convenient to use the results of geodesic measurements of the baseline distance d and the azimuth B.

We convert from the sphereical equatorial coordinates of the object d and δ, to the horizon coordinates - the azimuth A and zenith distance Z by using the well-known equations of spherical astronomy:

$$tg A = \frac{\sin t}{\cos t \sin \varphi - tg \delta \cos \varphi}, \quad \cos Z = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos t, \tag{3}$$

where $t = S - \alpha$ is the hour angle of the object; S is the sidereal time at the given observation point at time t; φ is the latitude of the observation point; A is the astronomical azimuth measured from the south point toward the west.

The calculations carried out for both points at each time t give two pairs of coordinates A_1, Z_1 and A_2, Z_2.

We have from the equations for five elements and the sines:

$$tg C = \frac{\sin B}{tg \varphi_2 \sin \alpha - \cos \alpha \cos B}. \tag{4}$$

On the celestial sphere (fig. 4), let Z be the zenith of point, M, O the position of the object seen from M, K the intersection of the direction from the point M to the point E with the celestial sphere.

Then $KO = \beta$, $ZO = Z_1$

Obviously, $KZ = 90° + \varphi$, where (for $d \ll R$): /10

$$\varphi' = \frac{d}{2R}. \tag{5}$$

The angle KZO equals the difference in azimuth of the object and point K Thus(Figure 5):

$$\Delta A = A - (180 + C). \tag{6}$$

We obtain β with the law of cosines from triangle KZO:

$$\cos \beta = \sin \varphi' \cos Z_1 + \cos \varphi' \sin Z_1 \cos \Delta A. \tag{7}$$

Substituting β into (2), we obtain D - the distance from the observation point E to the object. The altitude H of the object above the surface of the earth is now easily obtained:

$$H = D \cos Z_2 + \frac{D^2 \sin^2 Z_2}{2R}. \quad (8)$$

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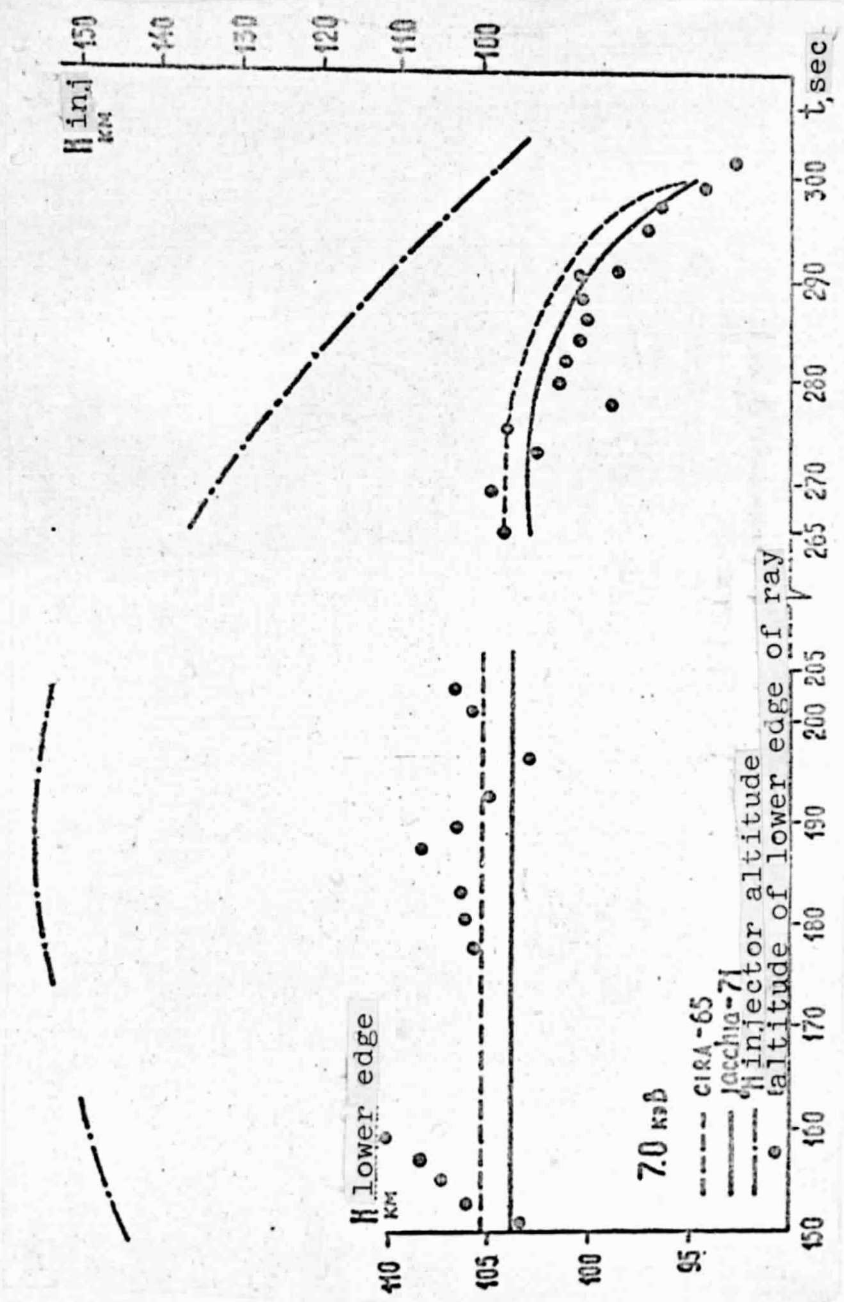

Figure 1. Values of the altitudes of the lower edge of artificial auroral rays (left altitude scale) and altitudes of the rocket with the electron injector (right scale) at the corresponding times. Calculations of the maximum penetration depth of electrons with E=7.0 keV for the CIRA-65 and Jacchia-71 models.

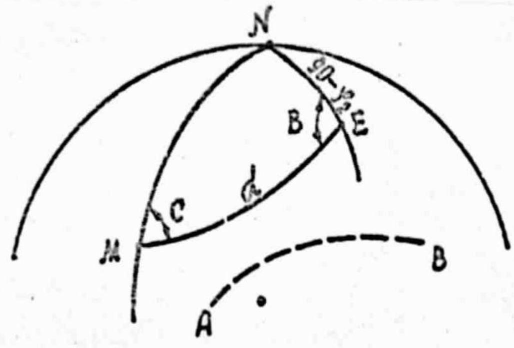

Figure 2. Relative position of optical observation points M and E, the north pole N and the projection of the trajectory of the lower edge of the artificial auroral ray.

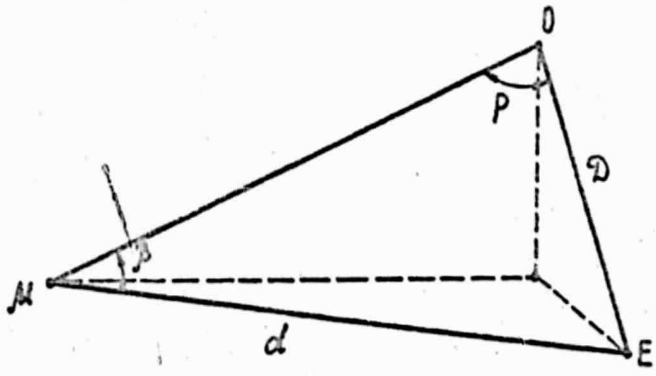

Figure 3. Plane triangle for determining the distance of the observational point E to the object.

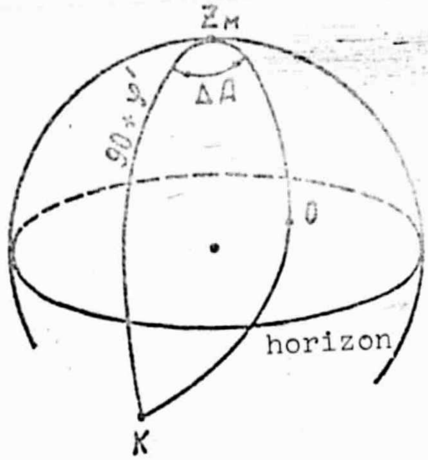

Figure 4. Position on the celestial sphere of the zenith Z of point M and the apparent position of the object O from point M. K is the intersection of the direction from the point M to point E with the celestial sphere.

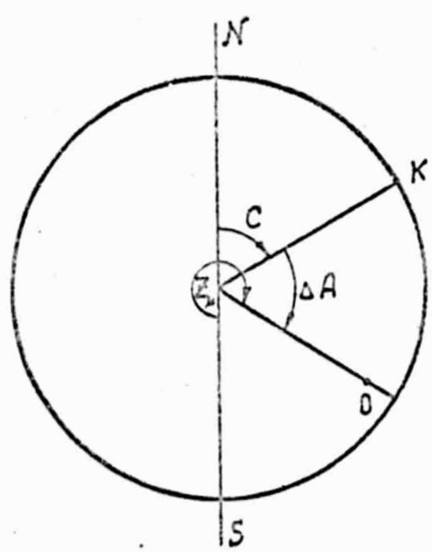

Figure 5. Relative position of the azimuths of the object O and the point of intersection of the direction from the point M to point E with the celestial sphere K.